

EXPLORING THE BOMBARDMENT HISTORY OF THE MOON

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The Moon is unique. It is the only object in the solar system that is both relatively accessible and still bears evidence, in the form of craters, shocked materials, and regolith, from practically every epoch of solar system history. This is both a challenge and a blessing. It is challenging because to understand the Moon's internal structure, chemistry, and complex resurfacing and bombardment history, we need to understand the formation and evolution of the solar system as a whole. It is a blessing because the Moon is a treasure trove of information for the study of the events that have shaped the Earth and other planets during most of their histories. To understand the Moon, we must study the planets, and to understand the planets, we must study the Moon.

The critical importance of interpreting the bombardment history of the Moon was identified by the **National Research Council's 2007 Space Studies Board** in their report, "**The Scientific Context for the Exploration of the Moon**" (hereafter the *SSB Report* [1]); they made it their *top science goal*. The SSB Report pointed out that the Moon's bombardment history is intimately and uniquely intertwined with that of Earth, with impact events strongly affecting the origin and evolution of our atmosphere, environment, and the prospects for habitability/early life. Moreover, links between surface crater density and radiometric ages, discovered on the Moon, serve as the basis for estimating surface ages for other solid bodies (e.g., Mars). Thus, the lunar cratering record is the key to probing the nature of events across the solar system. Finally, understanding the impact flux history recorded on the Moon gives us an idea of whether future catastrophic impacts are likely to affect the Earth or, on a different scale, how impacts from small particles should affect the planning for human space-flight missions.

While the recommendations given here mirror those of the SSB, we point out that this white paper is the consensus of the listed authors. Moreover, our recommendations are also consistent with those from LPI's 2006 Planetary Chronology Workshop (N. Barlow, personal communication). For this reason, the format of this white paper emphasizes the SSB Report's top science goals, namely the issues related to the bombardment history of the Moon.

SSB Science Goal 1a—Test the cataclysm hypothesis by determining the spacing in time of the creation of lunar basins.

Since the time of the Apollo Moon landings 40 years ago, there has been intense debate in the literature concerning the nature of the lunar impact record from 4.5-3.8 billion years ago (Ga). The debate has centered on a period of time referred to as the "Late Heavy Bombardment" or LHB, a phase in lunar history that occurred roughly 4.0 to 3.8 Ga (e.g., [2]). It marks the final epoch when the dominant surface geology of the Moon was created by large impacts. A few lunar basins, defined here as diameter $D > 300$ km craters, are known to have formed over this time period (e.g., Serenitatis, Imbrium). Many others that are stratigraphically older than Serenitatis or Imbrium lack critical age constraints and may or may not have been part of the LHB (e.g., [3, 4]).

The controversy is based on whether the LHB was the tail end of terrestrial planetary accretion (i.e., a "declining bombardment" that lasted ~700 My, with the youngest part being the LHB) or a "spike" in the impact rate occurring roughly 3.9 Ga and lasting ~100-200 My (i.e., "terminal cataclysm") [5]. *We are still unable to observationally distinguish between these two fundamentally different histories of the solar system.* Resolving the debate has been further hampered by the possibility that many Apollo samples have been biased by ejecta from the Imbrium impact ([6]). Nevertheless, a firmer understanding of this component of lunar history is critical to our understanding of the chronology of the solar system. Indeed, as described below, it may supply vital clues to unraveling the temporal evolution of the planetary system as a whole as well as how and when the planets reached their final orbital configuration.

The duration of basin-forming activity on the Moon is uncertain. Thus far, we only have one solid age and five tentative ages for the 15 basins produced during the Nectarian and Early

Imbrian periods of lunar history [1,3]. Based on those ages, estimates for the duration of a putative LHB range from 20 to 200 Ma. As we have no ages for ≥ 29 older, pre-Nectarian basins, we still have no idea if they are part of a lunar cataclysm or are instead part of the declining bombardment. As discussed below, this makes any basin older than Serenitatis a ripe target for sample return, with the highest priority being unaltered impact melt from the **South Pole-Aitken (SPA) Basin** [1]. Because SPA may be the oldest and may be the largest basin, it defines the beginning of the basin-forming epoch.

To demonstrate the potential importance of the LHB to the evolution of the planets, it is instructive to consider what it would mean if the putative lunar cataclysm did indeed occur. The

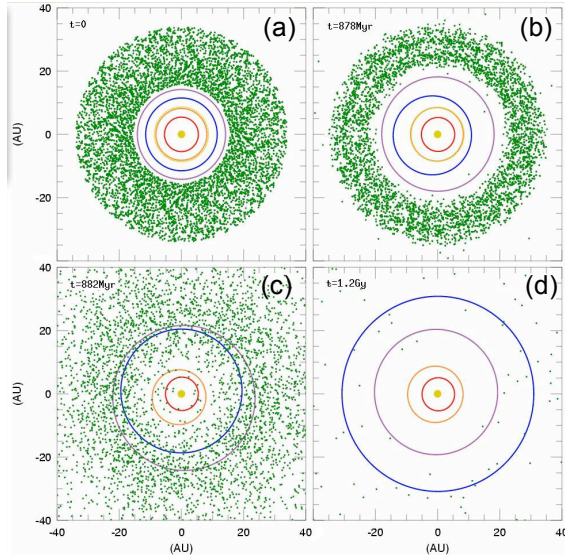


Figure 1: Planetary orbits and disk particle positions in the Nice model. The panels show four different times from a reference simulation. In this run, the giant planets were initially on nearly-circular, co-planar orbits with semi-major axes of 5.5, 8.2, 11.5, and 14.2 AU. The initial disk contained 35 Earth masses between 15.5 and 34 AU. (a) Beginning of planetary migration (100 My), (b) Just prior to the LHB (879 My in this simulation), (c) During the LHB (882 My) and (d) 200 My later, with the final planet orbits.

only way to create a cataclysm is to suddenly destabilize one or more small body reservoirs. A plausible candidate for this destabilizing event is planetesimal-driven giant planet migration. Evidence in the Kuiper belt's structure strongly suggests that the four outer giant planets were formed in a more compact configuration than they are today, and at some point in the early history of the solar system they migrated to their current orbits (e.g., [7]).

These concepts, combined with new ideas about planet formation processes, have recently been developed into a solar system evolution scenario called the “Nice model” [8,9,10] that provides a plausible means for producing a terminal cataclysm. In the Nice model, the giant planets are assumed to have formed in a compact configuration (all located between 5 and 15 AU, see [10] for justifications of these initial conditions; Fig. 1). Slow migration of the planets was induced by gravitational interactions with planetesimals leaking out of a ~ 35 Earth mass primordial disk of small bodies, the ancestor of today's Kuiper belt, residing between ~ 16 and 34 AU. After

hundreds of millions of years, Jupiter and Saturn crossed their mutual 1:2 mean motion resonance (the location where the ratio of their orbital periods equals 1/2). This event triggered an instability that led to a violent reorganization of the outer solar system. Uranus and Neptune penetrated the trans-planetary disk, scattering its members throughout the solar system. The interaction between the ice giants and the planetesimals damped the orbits of these planets — thereby leading them to evolve onto nearly-circular orbits at their current locations.

We cannot say whether the Nice model represents real events, but it is compelling to test this model for many reasons. First, it quantitatively explains many fundamental characteristics of the solar system (e.g., orbits of the Jovian planets [8], formation of the Trojans [9] and irregular satellites of the Jovian planets [11], the orbital signature of the Kuiper belt and scattered disk [12], and the curious presence of dormant-comet-like objects in the outer asteroid belt [13]). Second, if a cataclysm did occur, it naturally explains the ~ 500 My delay between the planet formation era and the onset of the LHB (see Fig. 2). Third, although the Nice model argues that

the LHB was triggered in the outer solar system, it does allow for most of the lunar impactors, particularly at late times, to originate from the asteroid belt as resonances driven by planet migration sweep the main belt ([10,14]). This is consistent with the arguments of [15] that the size-frequency distribution of lunar highland craters implies a main-belt asteroid source and is also consistent with geochemical data [16]. On the other hand, if the LHB was indeed the tail end of a “declining bombardment”, many of the Nice model’s attributes might turn out to be a mirage.

Thus, the Moon, either via the Nice model or some competing model, potentially allows us to understand the last stages of planet formation throughout the solar system. To test this tantalizing hypothesis, however, we need to determine the magnitude and duration of the lunar bombardment. Dynamically, this means further probing planet formation processes to see how constraints from the Moon and other objects (e.g., Mars, asteroid belt, outer planet satellites) fit together within a global model. Geochemically, this means collecting impact melts unambiguously tied to large craters and basins, and minerals thermally affected by impacts, for detailed petrologic, geochemical, and geochronological analyses. These samples should be selected to represent the entire distribution of stratigraphic ages among basin-forming events, and of lunar geographic locations. These same rocks and minerals also hold the potential to constrain the source of projectiles and their chemical compositions.

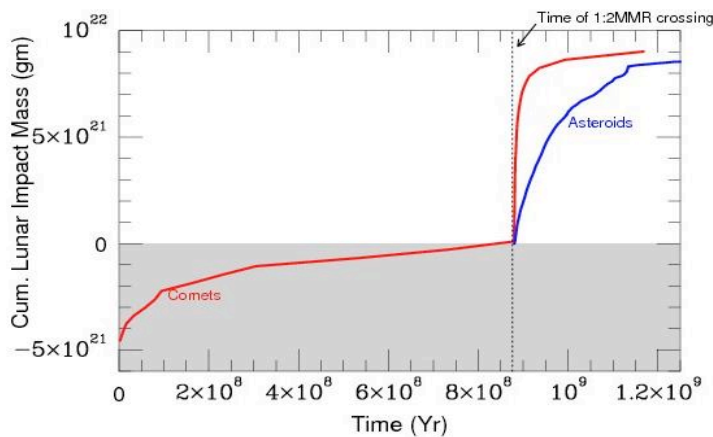


Figure 2: The cumulative mass of comets and asteroids accreted by the Moon in one run of Gomes et al. (2005). In order to emphasize the pre- and post-LHB eras, the comet curve has been arbitrarily offset so that the value is zero at the time of the LHB. 5×10^{21} g in comets strikes the Moon before resonance crossing and an additional 9×10^{21} g impacts the Moon afterwards, i.e., during the LHB. A comparable mass of asteroids collides with the Moon, but over a much longer timescale in this simulation.

Other than SPA (see below), a panel discussion at an LRO science targeting meeting (see [17, 18]) suggested that candidate target regions for impact melt samples include the **Nubium Basin** (middle pre-Nectarian, defined as a basin stratigraphically older than Nectaris basin), **Smythii Basin** (slightly younger), and **Apollo Basin** (the last of the pre-Nectarian basins). The timing of the latter third of the basin-forming events is better understood because of the availability of Apollo and Luna samples, but links between specific samples of known ages and specific basins is still fraught with uncertainty. For that reason, new or additional samples of impact melt from the **Nectaris**, **Serenitatis**, **Crisium**, **Schrödinger**, and **Oriente** basins are required. Oriente Basin is a particularly attractive target because it is the youngest basin and exquisitely preserved, so that the geological relationships between target rocks and impact lithologies should be mostly unambiguous and can be mapped geologically to confirm stratigraphic relationships between events. That clarity will dramatically assist with investigations of samples from older basins. Additional basins for exploration, suggested by Apollo 17 astronaut H. Schmitt, include **Tranquillitatis** and **Fecunditatis**.

An important lesson-learned from the Apollo era concerns the selection of multiple sample locations. The Apollo landing sites covered a relatively small region of the lunar surface. An ongoing controversy has been whether or not samples which purport to date the LHB are substantially contaminated by a single local event, namely the formation of the Imbrium impact

basin [6]. Ensuring spatial diversity of sample locations would potentially mitigate the development of similar future controversies.

Other than sample return, [18] suggests that targeting particular regions for new crater counts (e.g., old basaltic flows; basin ejecta) using LRO data may allow us to determine additional stratigraphic/mineralogical/elemental relationships that can help bound basin ages. Note that many regions of the Moon, particularly pre-Nectarian terrains on the lunar farside, have not been studied at LRO-level resolution under ideal lighting conditions.

We close this section by pointing out a few applications of this work that may allow us to address profound science questions beyond the Moon. Consider the following examples:

- Widely-adopted chronologies for Mars have the Early-Noachian period extending from ~4.1 Ga back to ~4.3 Ga or earlier. If most lunar basins formed < 4.0 Ga, however, that would likely be true for Mars as well. Thus, martian Noachian history, and all of its activity, might be squeezed down from hundreds of My to a mere ~100 My or less.
- The majority of martian volatiles (e.g., water) could have been delivered by comets and/or hydrated asteroids during the LHB [e.g., 10,19].
- The impact flux on the early Earth between 4.5 and 3.5 Ga, which is recorded on the Moon but has been erased by terrestrial geological processes, can be used to understand the impact regime under which life became established on our planet (e.g., [20]).

SSB Science Goal 1b—Anchor the early Earth-Moon impact flux curve by determining the age of (perhaps) the oldest and largest lunar basin (South Pole-Aitken Basin).

The pre-Nectarian period is the time span beginning with the formation of the Moon and ending with the impact of the Nectaris basin, which probably occurred around 3.92 Ga to 4.1 Ga [3]. The precise age of this basin and thus the timing of the end of the Nectarian is hotly disputed. Since the oldest age of solid lunar surface material determined so far is ~4.5 Ga, the pre-Nectarian period could be 600 million years long. On the other hand, the interval recorded by basins could be far shorter if topography was erased by a magma ocean or by a slushy, low viscosity crust.

Our knowledge of the pre-Nectarian system stems from the identification of some 30 stratigraphically old non-mascon multi-ring basins, including the oldest known basin, the South Pole-Aitken Basin (SPA) [1,3]. Some argue that basins older and much more degraded than SPA may still exist (e.g., [3,4]), but data from LRO and GRAIL may be needed to confirm this. Unfortunately, it is impossible at this time to directly relate dated pre-Nectarian rock clasts to any specific pre-Nectarian geologic surface unit, because subsequent multiple impact events displaced these samples from their original geographic location after formation. The relative ages of most pre-Nectarian multi-ring basins are based on crater counts on their floors or ejecta blankets. On the basis of crater counts and assumed impact rates, it has been suggested that no multi-ring basins older than 4.2 Ga are unequivocally recorded [3]. However, such ages are poorly constrained because even an approximate age for SPA has not yet been determined by analysis of returned samples. As the oldest multi-ring impact basins are critical calibration points for lunar chronology, this has implications for *other planetary surfaces whose inferred surface ages are linked to lunar data via crater counts*. Therefore, it is of critical importance to date the oldest generally recognized impact basin in order to derive the beginning of the Moon's bombardment history.

Note that if one could date all the lunar basins that ever formed, dynamical models suggest we would likely find a bimodal distribution of ages – one cluster associated with the LHB at ~3.9 Ga, and the other, at much older ages, associated with remnants or stragglers from the epoch of terrestrial planet formation (provided that remnants persisted until after the initial lunar crust had

solidified). SPA is a prominent candidate for having formed from impacts via the dregs of terrestrial planet formation. The implications of different SPA ages are as follows:

- If SPA was found to have an older age, say 4.2-4.4 Ga (e.g., [3,4]), then pre-Nectarian basins with successively younger relative ages need to be sampled to determine if a cataclysm began in the pre-Nectarian and, if so, when it began in that basin-forming sequence.
- If SPA was part of an LHB “cataclysm”, then the magnitude of the bombardment event is greater than previously proposed and our models of solar system formation will need to undergo revision.

In this context, it is useful to recall that the Moon faithfully records events during Earth’s Hadean Eon that relate directly to the period when the molecular precursors to life emerged.

SSB Science Goal 1c—Establish a precise absolute chronology.

Most lunar craters were formed by asteroidal or cometary impactors. *Relative* geological ages are determined by overlapping relationships and the spatial densities of craters, with older surfaces having accumulated more craters than younger ones. By calibrating crater counts with radiometric ages of returned lunar samples, believed to be derived from particular cratered surfaces, absolute chronologies have been developed (cf. [3,21,22]). However, they are beset by major problems:

- The association of dated rocks with specific impact (or volcanic) events is often uncertain, especially for ancient lunar basins.
- Before 3-3.5 Ga, the impactor flux was much higher and rapidly decayed in time, but evidence indicates it may not have decreased smoothly from 3.75 Ga.
- We currently have no ages for Late Imbrian and Eratosthenian impact craters.
- There are few radiometric ages spanning the last 1 Gy and few between 1 and 3 Ga. Those crater ages that do exist (109 Ma for Tycho; 800 Ma for Copernicus) are based on data that indirectly correlate with those cratering events.

To transcend these limitations, we need better data from the Moon and a better sense of how the impact flux has changed across the solar system over time. As outlined at a panel discussion at an LRO science targeting meeting [e.g., 17,18], one way to quantify the lunar impact flux is to obtain precise analyses of impact ages from a moderate number of post-3.8 Ga impact craters and an accurate determination of the relative number of impact events that occurred between those absolute benchmarks.

To begin constraining the Late Imbrian, samples are needed from craters that meet target requirements, such as **Humboldt**, **Tsiolkovskiy**, **Antoniadi**, and **Archimedes**. Eratosthenian craters that meet target requirements include **Hausen**, **Pythagoras**, **Theophilus**, **Eratosthenes**, and **Maunder**. The ages of younger impact events during the Copernican Period are also ill-defined, although tentative ages of 1.29 Ga, 0.8 Ga, and 0.1 Ga have been suggested for Autolycus (or Aristillus), Copernicus, and Tycho, respectively, based on samples that are interpreted to be distal ejecta of these and a secondary-impact-generated landslide. To confirm those ages and to further refine the flux during the Copernican, well-documented impact melt samples from **Kepler**, **Aristarchus**, **King**, **Copernicus**, and **Tycho** are needed.

Alternatively, approximate ages can be determined by estimating the impact rates for bodies that form craters of specific sizes (using known scaling between crater size and impactor size) to convert a geologic unit’s crater density into an absolute age. The widespread cratering of the lunar surface then overcomes the scarcity of radiometric ages. Modern dynamical models, coupled to the available constraints from the Moon, asteroid belt, Mars, the Kuiper belt, etc. give us reassurance that we will soon be able to construct a far superior crater chronology than exists

today across the solar system [e.g., 10]. The ramifications of this to our fundamental understanding of what makes a solar system “tick” cannot be overstated.

Additional science goals that affect our determination of lunar chronology include understanding the role of secondary craters on crater counts, latitudinal and apex/antapex asymmetries in crater counts; and crater formation as a process in itself (which allows us to compute scaling relationships between impactors and craters).

Science Goal 1d—Assess the recent impact flux.

In this goal, “recent” depends on the science question asked; the last several Gy, which can help us understand the evolution of life on Earth, and the last several tens of My, which can help us probe more recent events and constrain the present-day hazard to human life from impacts.

Several lines of evidence indicate the majority of lunar impacts over the past 3 Gy have been by asteroids, not comets (e.g., [23]). Most Earth-impacting asteroids originate in the main asteroid belt, where they are affected by both collisions and dynamical processes. Models of the evolution of the asteroid belt have shown that the lunar impact rate must have been changing over time, with peaks and valleys controlled by the major catastrophic collisions that break up some of the larger asteroids, creating numerous fragments that can be seen in today’s asteroid belt as so-called families. In fact, > 90% by number of main-belt asteroids with diameter $D > 1$ km are family members and so family members currently dominate the lunar impactor population. Hence, characterizing this dominant, stochastic component of the lunar impact record is crucial for any attempt to determine an accurate lunar chronology. The Moon can also help us determine whether asteroid disruption events are connected to impact-induced mass extinction events on Earth (e.g., “asteroid showers” and the Cretaceous/Tertiary [K/T] event [24,25]).

Even though comets have contributed only modestly to the Moon’s overall cratering record over the last 3 billion years, they may still have been an important source of volatiles. Indeed, if near-surface ice or hydrated phyllosilicates are found in deep polar craters, a substantial fraction of the water may have come from such comets (or hydrated C/D/P-type asteroids). Gain or loss of volatiles in impacts depends on factors like the impact velocity, which can be determined by detailed dynamical calculations.

Finally, the flux of small particles striking the Moon is important to understanding lunar regolith processes as well as the nature of the hazard to humans and equipment on the surface of the Moon (or some other interesting world to be explored). The Moon is constantly being hit by tiny particles with high kinetic energies produced by both comets and asteroids. Meteor showers created by disrupted comets and asteroids also bombard the Moon with dust-sized particles at particular times. Unlike the Earth, however, these particles are not stopped by any atmosphere. This hazard must be dealt with if humans are to spend long intervals in space or at an outpost exposed to space.

Conclusions

The *SSB Report* [1] concluded their report by prioritizing the 35 science goals that could be addressed, at least in part, within the then-existing Vision of Space Exploration. The top three highest-priority lunar science goals were all about exploring the lunar bombardment. They are:

1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins. The history of impacts in the early Earth-Moon system, in particular around 3.9 Ga, the time that life was emerging on Earth, is a critical chapter in terrestrial planet evolution. Understanding this period is important for several reasons: As tests of our models of the impact rate, planetary accretion, dominant environmental conditions at the Earth’s surface, impact frustration or encouragement of life, magma ocean formation and evolution, and extension and

verification of the chronology. In order to answer the question of whether there was a cataclysm at 3.9 Ga, sample returns from the oldest impact basins, and a spectrum of basins in between, combined with high-resolution imaging from orbit are required.

1b. Anchor the early Earth-Moon impact flux curve by determining the age of the generally recognized oldest lunar basin (South Pole-Aitken Basin). Although the enormous South Pole-Aitken Basin is generally regarded as the “stratigraphically” oldest basin on the Moon, its absolute age is unconstrained. All models of the first few hundred million years of solar system history depend on whether the large basins are part of a decreasing flux of material swept up by growing planet embryos or a later separate pulse of planetesimal-sized bodies. Details of the lunar stratigraphy can be better defined by integrated high-resolution imagery and topography, but it is essential to provide an absolute date for the oldest basin, the South Pole-Aitken basin, with the type of precision that can be obtained only in Earth-based laboratories with returned samples.

1c. Establish a precise absolute chronology. A well-calibrated lunar chronology not only can be used to date unsampled lunar regions, but it can also be applied to date ancient surfaces of other planets in the inner solar system through modeling. An absolute lunar chronology is derived from combining lunar crater counts with radiometric sample ages and is thus the most precise—and in some cases the only—technique to date planetary surfaces for which samples have not been or cannot be obtained. In order to determine the precise shape of the lunar chronology curve, samples should be returned from several key benchmark craters, young lava flows, and old impact basins, which also need to be imaged at high spatial resolution.

Thus, while we emphasize that the Moon is itself a fascinating object, it must also be viewed as the “Rosetta Stone” for deciphering the histories of the other planets. We believe the Decadal Survey should closely examine this point and what the Moon can do for the rest of the solar system in their analysis. **Moreover, it is essential that NASA continue to support R&A programs that allow progress to be made on these priorities as well as initiate data analysis programs for on-going and upcoming lunar missions (e.g., LRO).**

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